

6.0      WATERWAYS EXPERIMENT STATION REPORT: LOCKPORT POWER  
PLANT SLUICE GATE AND CONTROLLING WORKS DISCHARGE  
EVALUATION

6.1      BACKGROUND

6.1.1    General

The first Technical Committee (1981) examined each of the component MSD ratings for discharge through the Lockport facilities. Included among those were the ratings for the Powerhouse sluice gates and for the gated Controlling Works located about 2 miles upstream. The First Technical Committee recommended that consideration be given to new analytical studies of the discharge ratings for both Lockport flow control components. In 1982 the Chicago District, USCE, arranged for the Waterways Experiment Station (WES) at Vicksburg to evaluate the discharge rating curves in use by MSD to determine flow rates through the sluice gates situated in the Powerhouse and the Controlling Works at Lockport.

6.1.1.1    Powerhouse Sluice Gates

The MSD ratings for the Powerhouse sluice gates are based on a hydraulic model study by Muga (1961). The First Technical Committee examined the discharge rating curves and tables in use by MSD for the Powerhouse sluice gates and the report, "The Lockport Sluice Gate Model Study" (1961) by B. J. Muga and drew several conclusions:

- a.    In adapting the Muga report results for its use, MSD ignored the effects of gate-opening arrangement when only one or two gates are open, and developed a single rating curve to represent all one or two-gate open combinations for the Powerhouse sluice gates.

- b. Likewise, MSD developed a single discharge rating for all three sluice gates open which ignored the fact that the model study found the discharge to be affected by the tailwater elevation. As before the rating was intended as a simplified representation for the full range of tailwater ratings.
- c. The exclusion of the trashrack and a representative forebay in Muga's model study probably resulted in bias in the computed discharge ratings for the prototype sluice gates.

#### 6.1.1.2 Controlling Works

Descriptive information concerning the rational basis for the rating curves used by MSD for computing discharge through the Controlling Works sluice gates is not available. However the computational sheets attached to the rating table, which bears a 1947 revision date, imply that the hydraulic principles of critical depth and minimum specific energy were in fact the basis.

The First Technical Committee concluded that the reliability of the MSD rating was questionable on several counts. These included:

- a. The absence of a quantitative description of the weir formed by the gate supporting structure.
- b. The contrary variation of the MSD equivalent broad-crested weir discharge coefficient with the  $h/b$  ratio.
- c. The affects of the large mooring piers on the gate ratings.
- d. The absence of a tailwater level gage and the adequacy of the upstream gage with respect to location.

- e. The possibility of tailwater submergence from the Des Plaines river.

## 6.2 WATERWAYS EXPERIMENT STATION REPORT

### 6.2.1 Scope

The scope of the WES report (1985), by E. Dale Hart and Richard G. Hart and Richard G. McGee, included:

- a. A review of the old power plant sluice gate model study (Muga, 1961), previous computations, drawings, and results.
- b. Recomputation of the rating curves considering structure features, hydraulic characteristics, and in the case of the power plant sluice gates, those features not considered in the model study, such as the trashracks.
- c. Determination of operational recommendations such as the sequence of gate openings.
- d. Determination of any needed monitoring revisions such as possible relocation of water-level gages.

### 6.2.2 Analysis

#### 6.2.2.1 Powerhouse Sluice Gates

The WES evaluation of flow through the Lockport Powerhouse sluice gates is based on a reanalysis of the Muga model data. Three flow-control conditions are defined to examine the discharge through the three converted turbine

pits that were modeled. The first two conditions, sluice gate control and draft tube control, are the same as previously described by Muga.

The third flow-control condition is introduced to compute flow for the special situation when the forebay water level drops such that flow passes through the sluice gates as free-surface flow and is constricted only by the sides (and bottom) of the gate structure. Generally this occurs when the  $H/b$  ratio falls below a value of about 1.2. Theoretically then, critical flow will occur when the forebay water level is lowered to -11.6 ft, CCD or less. As a check for Lockport conditions WES computed the discharge assuming both draft tube and critical flow-control conditions. The upper limit of application for the critical flow condition was determined to be -10 ft, CCD based on a graphical comparison the discharge vs. water level plots for the two conditions.

The data analysis takes into consideration the approach velocity head,  $V^2/2g$ , in determining the appropriate energy head,  $H_1$ , as well as account for energy losses through the trashracks. Neither of these factors were evaluated in the original model study.

Discharge rating tables are developed for all gate configurations for each flow-control condition. WES adopted the same three-digit notation previously used for gate opening configuration. MSD operating rules generally calls for gates to be fully closed or fully open in order to avoid vibrations which had been observed during partial gate opening operations. Therefore ratings for sluice-gate control conditions are developed for configurations 515, 155 or 551, or 151, and 115 or 511, for one or two of the three-gate set open. The digits 1 and 5 represent open and closed positions, respectively.

The total estimated error for discharge =  $\pm 7.1\%$ .

Recommendations include: calibration checks for the upper and lower pool water level gages, and field verification of the sluice gate discharge equations.

#### 6.2.2.2 Lockport Controlling Works

The WES analysis of the Controlling Works rating is a very comprehensive development of the discharge rating which addresses the concerns of the First Technical Committee.

Information on the geometry of the gate supporting structure, provided by the USCE Chicago District, was used to define the gate sill as a broad-crested weir of a length equal to nine feet and a height of one foot. The weir crest is -15.0 feet, CCD datum. The effective gate-opening width was computed for elevation -6 feet. The free flow discharge coefficient was determined to vary from 3.32 to 2.63 for water levels in the canal between +2.0 and -13.0 feet, CCD. The WES rating, compared to the MSD rating, varies in difference from 13 percent greater at +1.0 feet CCD to about 28 percent less for -10.0 feet CCD. For -6.0 feet CCD the MSD rating is about 6 percent greater. The flow through gates 6 and 7, closest to the north abutment, was found to be inhibited by the presence of the large mooring piers in the canal. Consequently the discharge for these gates is 0 to 2 percent less than for the other gates.

The WES analysis recognizes the possibility of submergence effects caused by tailwater conditions. For the purpose of applying corrections to the free flow discharges to account for downstream submergence the point of incipient submergence is assumed to be  $0.80 H_2/Y_d$ .

Discharge tables are presented for selected water levels in the canal ranging from +2.0 to -13.0 feet, CCD and with corrections applied for submerging tailwater levels. The latter is expressed for  $H_d/H_1$  values in increments of 0.005 from 0 to 0.20 ft/ft.

The report recommendations include: relocation of the upstream gage outside the drawdown zone, reestablishment of the downstream gage at a new location to acquire representative tailwater levels, suggestions for gate-opening sequence and configuration, and field verification of the ratings where possible.

### 6.3 TECHNICAL COMMITTEE FINDINGS

#### 6.3.1 Powerhouse Sluice Gate Ratings

The Technical Committee finds the WES analytical procedures to be technically sound and, except as previously noted, consistent with the ratings defined by Muga. However it is recognized that the WES study is constrained and limited by information contained in that report. The Muga report does not contain the original laboratory data. Except for a number of photographs the study results are summarized in the form of plotted figures and tables expressed in prototype units.

Apparently the adequacy of the model study, for the purpose of computing discharge, has not been questioned in the past. Neither is it questioned by the WES analysis. However a cursory examination of AVM and MSD records (not available to the WES study) involving flow through the Powerhouse sluice gates raises some doubts about the reliability of the model-defined discharge ratings and "control condition" transition from the sluice gates to the draft tubes.

The stated principal concerns of the model study dealt with (1) the general behavior and profile of flow through the turbine chamber, (2) wall pressures exerted on the housing located above the number four draft tube opening, and (3) discharge coefficients.

The study grew out of the MSD plan to remove turbines numbers 3, 4 and 7 and the miter gates controlling flow to the turbine chambers. The miter gates

would be replaced with a bulkhead fitted with sluice gates. The new sluice gates would regulate flow through the dam via the draft tube openings. In retrospect it appears that the main causes for concern on the part of MSD were the wall pressures that would be exerted on the turbine chamber housing above the No. 4 draft tube, and the consequences of closing the No. 4 tube. Subsequently the decision was made to close the tube because, among other reasons, the structural integrity of the housing near the entrance to the tube was unknown. Any possible effects of changing from the large miter gates to the smaller sluice gates on the discharge capacity apparently was not an issue.

A large portion of the experiments were run with the No. 4 draft tube open. The "control" for all of the "A" tests were the sluice gates, even when all three gates were fully open. The hydraulic capacity of the four open draft tubes (area = 288 square feet) was greater than the capacity for the three open sluice gates (area = 378 square feet) for all "A" experiments over the full range of water levels in the forebay. Whereas for the "B-III" experiments with the No. 4 tube closed (area of three remaining draft tube openings = 244 square feet) the hydraulic capacity of the three open sluice gates was greater than that for the draft tubes.

For the point of incipient transition from sluice gate to draft tube control the WES equations 1 and 2 are equal, and

$$C A \sqrt{2g H_1} = C^1 A \sqrt{2g \Delta H} \quad 6.1$$

where

$C$  = discharge coefficient, sluice gate

$A$  = sluice gate area

$C^1$  = discharge coefficient, overall structure

Referring to Figure 6.1

$$\Delta H = H_1 + H_d$$

where  $H_d$  = draft head, -28.42 - T.W., and

$$C^1 = C \sqrt{H_1} / (H_1 + H_d) \quad 6.2$$

The condition for incipient control transition can also be described to express the functional relation of the draft tube.

$$C A \sqrt{2g H_1} = C_d A_d \sqrt{2g \Delta H_d} \quad 6.3$$

where the subscript  $d$  refers to the draft tube.

The 1961 experiment seems to be primarily interested in the structural consequences of not closing the number four draft tube and the hydraulic impact of its closure. Attempts to determine the distribution of flow among the four draft tubes were unsuccessful both physically and analytically. The definition of control transition apparently was not of primary concern.

The rating curves for the sluice gates as defined by WES are not significantly different from the Muga ratings. As noted earlier, the availability of the AVM flow data provides a basis for insight to the adequacy of the model defined ratings for the Powerhouse sluice gates.

Storms in late February and again in early March 1985 and Oct 1986 caused high flows in the Sanitary and Ship Canal. During the 1985 flood the Powerhouse sluice gates were used in some fashion for 26 consecutive days. The Controlling Works gates were used during five days of the period. On February 25 and March 4, the USGS made current meter measurements of discharge. A cursory

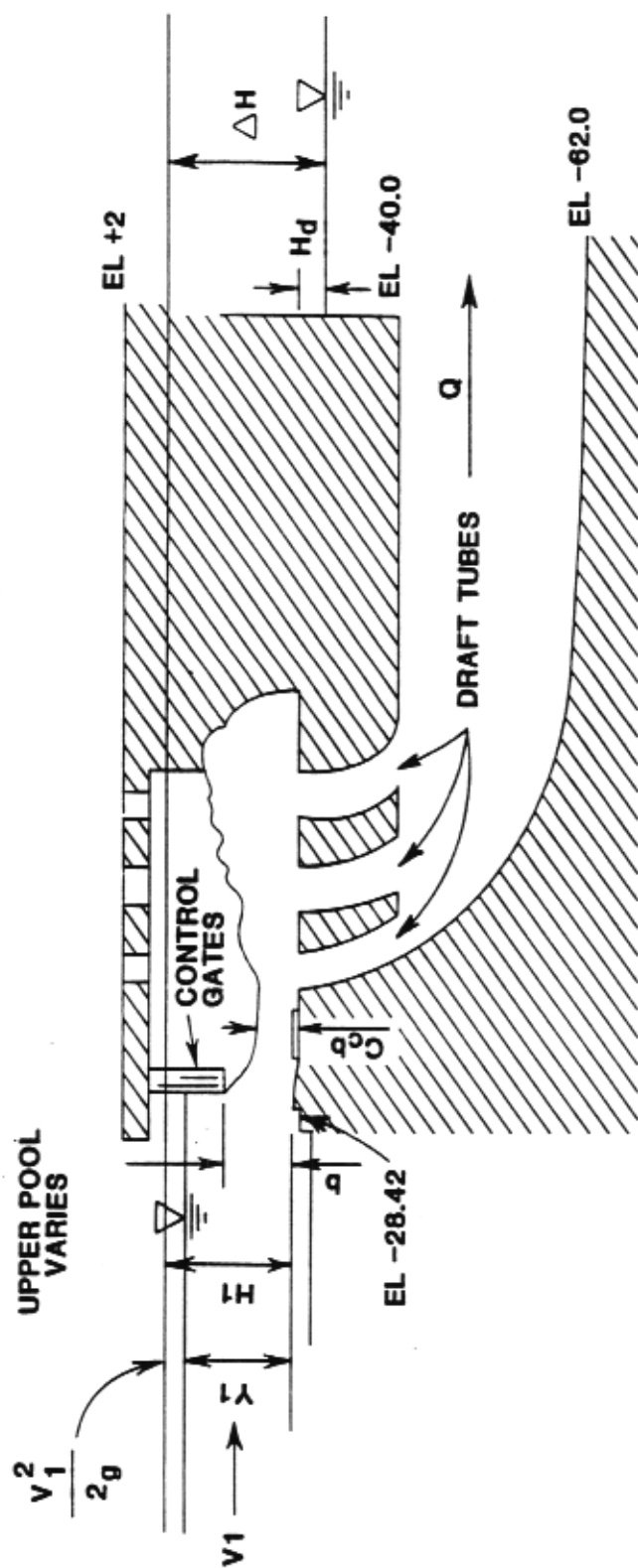


FIGURE 6.1

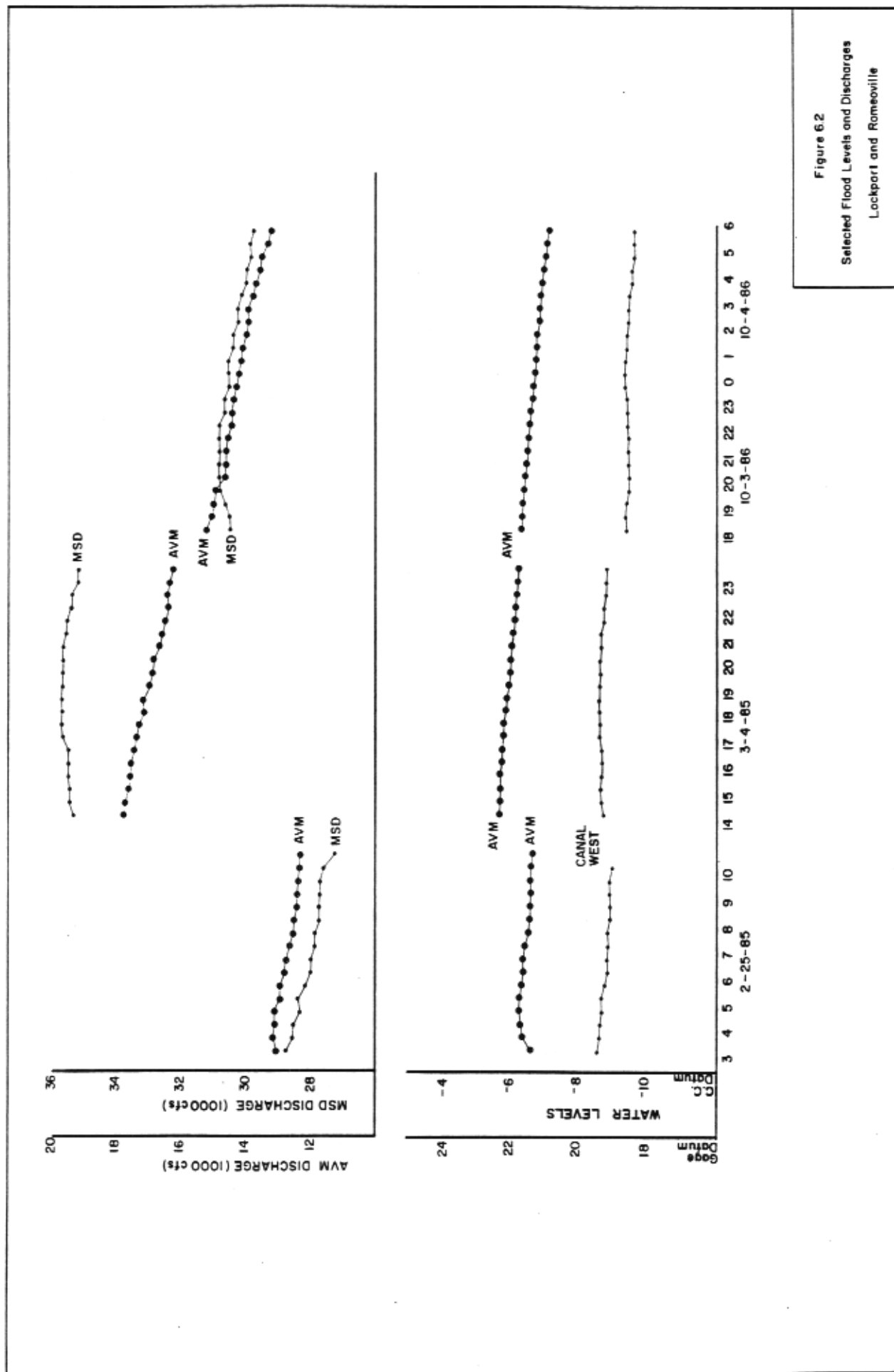
# LOCKPORT BAY SECTION

examination of the MSD Lockport and AVM records for these dates (Figure 6.2) tend to support the argument that the discharge ratings for the Powerhouse sluice gates may not be adequately represented by the model study.

On March 4, 1985 a high rate of flow was sustained for a period of about 9 hours when all Powerhouse and Controlling Works gates were open. Water levels fell gradually during the period with a total fall of only 0.5 ft at the AVM station and 0.05 ft at the Controlling Works and Powerhouse. A discharge of approximately 200 cfs to or from storage is required to cause a change in water level of 0.1 ft per hour in the Romeoville-Lockport reach. The discharge at the AVM site varied gradually from about 18,000 to 16,500 cfs during the 9-hour period on March 4, 1985 while the reported MSD discharge varied from 35,800 to 35,200 cfs. The MSD discharge included about 12,000 cfs through the Controlling Works and about 21,000 cfs through the Lockport Powerhouse sluice gates. Taking into consideration the probability of submergence effects and the observations cited in Section 6.1.3.2 the discharge through the Controlling Works was more likely to have been 5,000 to 6,000 cfs than the reported 12,000 cfs. This in turn suggests the flow through the Lockport Powerhouse sluice gates, based on AVM record, was considerably less than the 21,000 cfs indicated by the Powerhouse log and the WES curves.

Earlier on March 4, 1985 between midnight and 2 a.m. when gates A, B, and C in pit 7 and gate B in pit 4 were open, the flow reported at Lockport was about 13,000 cfs when the AVM flow was about 7,400 cfs. According to the MSD record (and supported by the WES report) the total flow through the Nos. 4 and 7 pit sluice gates was about 10,700 cfs rather than approximately 5,000 cfs that can be deduced from the AVM record.

The uncertainties concerning the Powerhouse sluice gate ratings is best illustrated by examining selected periods of concurrent record of water level and discharge for MSD Lockport and the Romeoville AVM. Three periods representing



storm runoff are available in which one or more of the Powerhouse pits are operated with all three sluice gates fully open for several hours. During each period the control configuration at Lockport, i.e., Powerhouse gates, turbines, and Controlling Works gates, was held relatively constant. The canal water levels in the Romeo-ville-Lockport reach varied gradually and the effects of changes in channel storage were small compared to the flow rate.

Water stages and discharges for February 25 and March 4, 1985 and October 3-4, 1986 are also plotted in Figure 6.2. The plotted data are taken directly from the Lockport Powerhouse log sheets and the AVM printout.

Data marking the beginning and end of the quasi-steady flow periods are given in Table 6.1. The MSD-reported flows through the Powerhouse and Controlling Works gates have been recomputed on the basis of the WES report. In the case of the Controlling Works gates a submergence ratio of 90 percent was assumed. This is consistent with observations made during the March 4, 1985 flood, and under similar conditions in 1982 and 1983. The water level readings for the Controlling Works gage are not plotted or listed because the reported levels are consistently 0.2 foot higher than the Canal West gage readings.

The MSD Lockport flows are listed for each control component; turbines, Powerhouse gates, and Controlling Works gates. The differences between the WES-adjusted MSD Lockport and AVM flows clearly are cause for concern regarding the adequacy of model defined discharge ratings for the Powerhouse sluice gates when all three gates are open to the former turbine chambers (B-111). There are other instances, for only one of the sluice gates open, when the MSD Lockport and AVM flows are in close agreement and tend to confirm the model rating B-515. The limited AVM records, for flow when two of the three sluice gates are open, are simply not suitable for drawing conclusions about the reliability of the model ratings B-151, B-115, and B-511.

TABLE 6.1  
COMPARISON OF MSD AND AVM WATER LEVELS<sup>1</sup> AND DISCHARGES<sup>2</sup>

Time	Water Level, in-ft			Discharge, in-cfs					
	Tail- water	Canal West	AVM	Tur- bine	Power- house	C.W.	Total	AVM	Diff.
February 25, 1985									
0315	-37.80	-8.45	21.45	1750	13950	7200	22900	13130	10910
1015	-38.45	-8.90	21.51	1800	14000	6300	22100	12480	12340
Ph gates 4ABC, 7ABC, and C.W. 1-7 open									
March 4, 1985									
1415	-36.65	-8.65	22.43	1830	20450	6500	28800	17890	9770
2315	-36.60	-8.70	21.94	1890	20410	6500	28800	16460	9620
Ph gates 3ABC, 4ABC, 7ABC, and C.W. 1-7 open									
October 3-4, 1986									
1815	-37.20	-9.30	21.81	4175	17930	5800	27900	15330	12570
0615	-37.60	-9.60	20.92	1830	17650	5400	24900	13380	11520
Ph gates 3AC, 4ABC, 7ABC, and C.W. 1-7 open									

<sup>1</sup> MSD Lockport CCD datum is 579.48 ft NGVD; AVM datum is 551.89 ft NGVD.

<sup>2</sup> MSD Powerhouse and Controlling Works records adjusted on basis of WES report, also 90% submergence for C.W. gates.

No attempt is made to make a detailed analysis of the runoff for the three storms considering the uncertainties of synchronous records and representative water stages. Nevertheless, if the estimated 200 cfs equivalence for 0.1 ft/hr change in channel storage is reasonable, it is unlikely that storage is a significant factor for the time periods under consideration.

A comparison of the total flows indicate differences on the order of 10,000 cfs or more depending on whether two or three of the pits are in operation. The large differences in discharge for the adjusted MSD Lockport and AVM flows suggest that the actual flow through the Powerhouse sluice gate pits, when all three gates are open, is considerably less than the model-based flow. This would still be the case even if the Controlling Works was fully submerged and the flow into the Des Plaines reduced to zero.

Current meter measurements were made on both February 25 and March 4, 1985 and no reason was found to question the validity of the recorded AVM flows given in the table. Other segments of concurrent record of flood runoff can be found in which only one or two of the three Powerhouse sluice gates are open. These instances suggest that the model-based discharge also may be greater than the actual discharge for one or two gates open. Although the indicated differences are small for the case of one gate open the paucity of data available at this time doesn't warrant speculation as to the magnitude of differences for the two gates open situation.

The model study did not provide a transition to "draft tube" control, nor its rating, which is representative of the prototype. Neither laboratory data nor a detailed description of the experimental procedures were included in the Muga report. The transition from sluice gate control to draft tube control was determined mainly by observing water levels within the turbine chamber relative to the gate position. Such a procedure would not be recommended for the expressed purpose of defining the control transition for a range of headwater levels and discharges.

- (1) The study presented by WES is precisely what is needed, from an analytical point, to put the Controlling Works rating in perspective. Appropriate technical references have been utilized to define the structure hydraulically, and to determine pertinent coefficients for free and submerged flow under normal conditions.

The four 30-ft diameter mooring piers (see Figure 6.3) were judged to have some influence on flow through the Controlling Works gates. This influence was expressed in terms of the velocity-head computed for the approach to the gates, and to account for head loss at pier no. 3 for the computation of flow through gates nos. 6 and 7.

- (2) Nevertheless there is some basis for suspecting that the mooring piers, together with other site considerations, may have a greater flow-inhibiting effect than would be expected otherwise. For example:
  - (a) During floods there is likely to be a concentration of flow with significant velocity along the levee approaching the north end of the structure (gate 7). From this direction the mooring piers could represent a formidable obstruction to flow.
  - (b) Ignoring the mooring piers for the moment, with any reasonable concentration of flow along the canal levee from the north, the structure is somewhat analogous to a constricted section with a large contraction ratio that is near fully eccentric. This would be particularly true if downstream

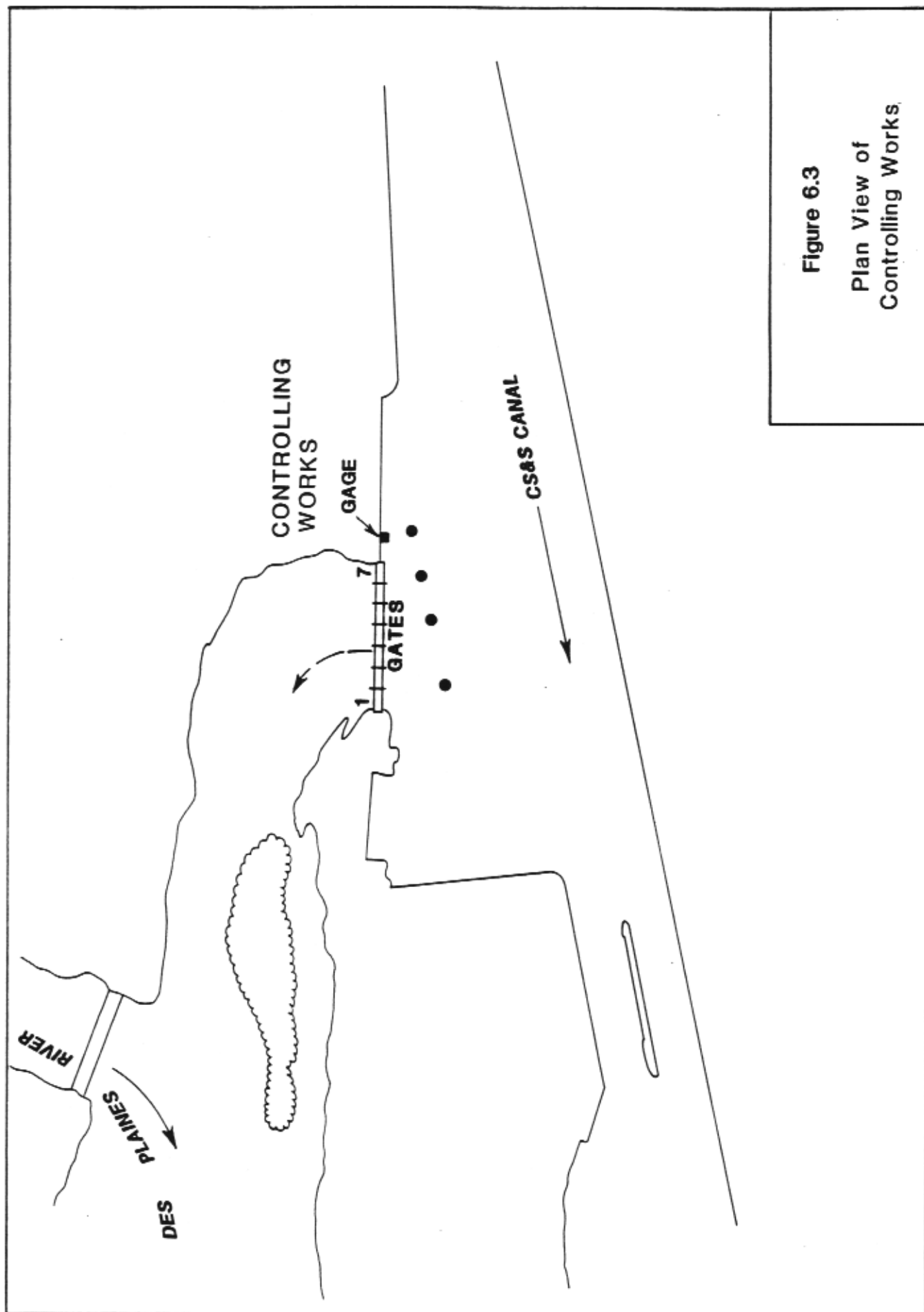


Figure 6.3  
Plan View of  
Controlling Works

submergence existed. Under these conditions the no. 6 and 7 gates could well be "outside" the live contracted zone, and it would not be unusual for flow through gates 6 and 7 to be relatively small. For comparable bridge constrictions (with subcritical flow) there have been many observations where flow in the "6 and 7" bents, or openings, were found to be zero or even negative. The presence of obstructions such as mooring piers would tend to limit the access of flow to this area even more.

- (c) The discharge channel connecting the downstream side of the Controlling Works with the Des Plaines River turns immediately to the left almost parallel to the canal. This, together with the probable influence of the mooring piers, gives cause to suspect more fall across the south abutment than the north abutment.
- (d) In a letter dated August 4, 1983 to the Chicago District, MSD reported that a water level gage had been installed on the downstream side (probably on the pier separating gates 3 and 4) to study submergence effects. Five major storms were studied from November 1982 to July 1983. Generally, the data shows values of the submergence ratio  $y_d/y_1$  to be greater than 0.85 whenever six or seven of the gates were in the open position, an indication of submergence. Apparently the downstream gage is not operational or has since been removed. The data attached to the letter was provided by MSD and contains nothing to suggest any caution in the use of the WES ratings.

- (e) On March 4, 1985 a large flood occurred at Lockport. All of the gates at the Controlling Works and Powerhouse sluice gate pits 4 and 7 were open by shortly after 2 a.m. the remaining sluice gates, pit no. 3, were opened before 9 a.m. Between 10 a.m. and 4 p.m. the USGS made two measurements at the Romeoville AVM gage. About 3 p.m. the current meter measurement and the AVM gage indicated a discharge of about 17,900 cfs at the Romeoville site when the Lockport Powerhouse log showed about 35,500 cfs (21,300 Powerhouse sluice gates, 12,300 Controlling Works).
  - (f) On March 4, 1985 a USGS field party inspected the Controlling Works at about 4 p.m. Observations at gates 6 and 7 found no visible flow through these two gates. After a visual estimate of about 1.5 to 2.0 ft of fall through gate 1, tapedowns from the most downstream abutment determined the fall to be 2.05 ft.
  - (g) Earlier on the same day, at 3:15 p.m., an engineer from the Chicago District visited the site. Although his observations, in the form of a notational sketch, are not quantitative, they do confirm the implied USGS notion that the relative flow and the fall through the individual gates from north to south (7 to 1), is small to large. In addition, the sketch indicates all of the mooring piers are within the area of drawdown to the structure and do exert some influence on the distribution of flow among the gates.
- (3) Representative upstream and downstream gages are essential for reliable monitoring of discharge at the Controlling Works.

- (4) According to the Chicago District the uncertainties of discharge and submergence effects at the Controlling Works may be more complicated than heretofore considered, based on a current and preliminary analysis by WES of the October 1986 flood. This analysis presents a compelling argument that during the October 1986 flood, when the Controlling Works gates were open, the direction of flow from the Sanitary and Ship Canal to the Des Plaines may have been reversed for a part of that time.

There is an awareness of the possibility for Des Plaines River flow to enter the Sanitary and Ship Canal through open Controlling Works gates if and when the water level for the Des Plaines is higher than the level in the canal. However, the Technical Committee's investigation has not yielded any substantive information to support the argument that such a reverse flow condition actually occurred. The matter has been discussed with MSD engineers. They concede the possibility, but have no evidence, pro or con, that the flow was reversed during the October 1986 flood, or for any previous flood.

#### 6.4 RECOMMENDATIONS

- (1) Assess the adequacy of the Lockport water level gages for the purpose of computing the discharge through the Powerhouse sluice gates using the WES ratings.
- (2) A site reconnaissance and evaluation should be made to determine the upstream and downstream water level gage requirements necessary to insure prudent application of the WES ratings for the Controlling Works.

- (3) Plan and execute a set of field measurements designed to verify, or modify if necessary, the WES ratings for both the Lockport Powerhouse sluice gates and the Controlling Works.
- (4) Assess the operating conditions for which reverse flow through the Controlling Works may possibly occur and the probable consequences in terms of diversion measurement and accounting.